Probabilistic Model of the Solar Energetic Particle Environment and Its Effects on Space Systems

M. A. Xapsos, T. Jordan, C. Stauffer, J. L. Barth, and R. A. Mewaldt

***Abstract*— A probabilistic model of the long-term solar energetic particle event environment is further developed for spacecraft design applications. Confidence-level based approaches for evaluating total ionizing dose, displacement damage and single event effects due to solar particle events are presented.**

Index Terms—solar particle event, space environment model, space weather, radiation effects

I. Introduction

Developing and implementing strategies to deal with the space radiation environment is critical for new robotic and manned exploration initiatives. In order to have reliable and cost-effective spacecraft design and implement new space technologies accurate models are needed for estimating radiation risks. Underestimating radiation levels leads to excessive risk and can result in degraded system performance and loss of mission lifetime. Overestimating radiation levels can lead to use of excessive shielding, reduced payloads, over-design and increased cost.

The space radiation environment consists of low energy plasma and three types of energetic radiations. The first is radiations trapped by planetary magnetic fields such as the Earth's Van Allen Belts. The second is the comparatively low-level flux of highly energetic ions that originate outside our solar system called galactic cosmic rays. The third is solar particle events, i.e., bursts of radiation emitted by the sun that are characterized by high fluxes of protons and heavy ions.

For new exploration initiatives to the moon and beyond, spacecraft are away from the protection of the Earth's magnetic field. Thus, galactic cosmic ray and solar particle event radiations are a particularly serious concern for spacecraft systems, instrumentation, and for astronaut exposure.

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There are at least two established models of the galactic cosmic ray environment – the Moscow State University model [1] that is incorporated in the CREME96 program suite [2], and the NASA model of Badhwar and O'Neill [3]. Both models implement a solar modulation description to characterize the transport of galactic cosmic rays into the heliosphere and to the near-Earth region. The two models are generally in reasonable agreement [4].

Galactic cosmic ray fluxes have traditionally been used to evaluate long-term Single Event Effects (SEE) rates in microelectronics and photonics systems of spacecraft. Recently, however, it was shown that long-term accumulated solar particle event fluences exceed accumulated galactic cosmic ray fluences during the solar maximum time period at shielding levels often considered for spacecraft design [5]. This emphasizes the importance of further understanding the long-term solar heavy ion environment for SEE applications. This is now a more realistic goal than in the past because the difficulty of resolving heavy elements in space experiments at the high flux rates observed during solar events has been overcome with modern instrumentation such as that onboard the Advanced Composition Explorer (ACE).

Besides SEE, the radiation effects that solar energetic particles have on spacecraft electronic and photonic systems generally fall into two other categories – total ionizing dose (TID) effects and displacement damage (DD) effects. Although models of cumulative solar *proton* event fluences have been available for some time [6-8] for the study of these latter two radiation effects, ions heavier than protons are not generally included in these analyses due to limited knowledge of the long-term solar heavy ion environment. There are nonetheless indications this should be done under some circumstances [9].

Spacecraft design from a radiation effects viewpoint is often based on estimating the average and worst case environments and assigning a margin to the average. In this paper we emphasize the probabilistic approach to spacecraft design. The probabilistic implementation is an advance because it supplies more complete information to the designer, allowing risk-cost-performance tradeoffs to be evaluated. Probabilistic approaches for evaluation of TID, DD and SEE effects are presented based on our solar energetic particle environment model, which is developed further here by extending the range of the particle energy spectra. This approach makes high confidence level designs possible in addition to designs based on the average environment.

II. Data and Methods

A. Solar Particle Event Environment

All naturally occurring elements ranging from protons to uranium are present in solar particle events. The solar particle data used in our model are compiled from analyses of long-term satellite data from a number of sources. The data base for solar protons is most extensive, incorporating measurements made on the Interplanetary Monitoring Platform (IMP) and Geostationary Operational Environmental Satellites (GOES) series of spacecraft spanning a time period from 1966 to 2001. Probability distributions for solar proton event magnitudes and cumulative fluences are derived from Maximum Entropy Theory [10], providing a mathematical basis for selection of probability distributions. One of the advantages of our proton data base is that it extends to energies of over 300 MeV, which is considerably higher than other solar proton models. This is significant for proton-induced SEE, TID and DD effects in heavily shielded regions of spacecraft, as well as for astronaut exposure. The solar proton energy spectrum is calculated for a given confidence level and mission duration.

The data for alpha particles were processed in a manner similar to the proton data by combining the best features of the Goddard Medium Energy (GME) data from the IMP-8 satellite and the Space Environment Monitor (SEM) instrumentation from GOES satellites. The combined data cover the time period from 1973 to 2001. The resulting alpha particle energy spectra derived from the combined instrumentation have been summed up for the solar maximum periods and compared to the analogous solar proton energy spectrum over the same time period and from the same instrumentation to allow the long-term alpha particle energy spectrum to be scaled relative to the proton energy spectrum.

In a similar fashion the model energy spectra of the most abundant heavy elements with $Z > 2$ are calculated relative to the alpha particle energy spectrum, using data from the Solar Isotope Spectrometer (SIS) instrument onboard the ACE spacecraft. This has been operational since 1997 and the data used in the current model cover the most recent 7-year solar maximum time period. The available energy spectra measured by this instrumentation are for alpha particles, C, N, O, Ne, Mg, Si, S and Fe.

In the current paper the energy spectra of the above 9 major elements plus protons have been extended down to 0.1 MeV per nucleon based on the Electron, Proton, Alpha Monitor (EPAM) and Ultra Low Energy Isotope Spectrometer (ULEIS) instrumentation onboard ACE, as described by Mewaldt [11]. This allows improved environment estimates to be made for lightly shielded devices on the surface of spacecraft such as solar cells or lightly shielded detectors and instrumentation. Thus, all the abundant elements in the solar energetic particle environment are now described in our model by wide ranging energy spectra that are based on long-term satellite measurements.

Some of the remaining minor elements in the Periodic Table (Z = 11, 13, 15, 17-20, 22, 24, 28, 30) are characterized in our model based on measurements from the International Sun-Earth Explorer-3 (ISEE-3) spacecraft that occurred over a 14-year period [12]. The remaining minor elements were determined from an abundance model based on current knowledge of solar photospheric abundances [13] and processes [14]. In all, 83 of the 92 naturally occurring elements in the Periodic Table are included in the model. The 9 elements for which data are not available are expected to have a negligible effect on results. Further details are described in [5].

B. Total Ionizing Dose Evaluation

TID in microelectronic components is cumulative radiation damage resulting from ionization or electron-hole pair formation in insulating regions of devices. It can cause threshold voltage shifts in transistors, leakage currents and timing skews in circuits.

In order to evaluate the TID deposited by solar particle events over a period of time corresponding to a space mission, the assumption is made that the device is at the center of solid sphere aluminum shielding. The code NOVICE [15] is used to transport the incident ion energy spectra to the device, assuming isotropic incidence. The dose is then calculated

$$Dose = C\sum_{Z=1}^{92} \int_E L(E)\varphi(E)dE \qquad (1)$$

where $L(E)$ and $\varphi(E)$ are the transported particle linear energy transfer (LET) and fluence, respectively, as a function of energy, and C is a unit conversion. The total deposited dose is a sum over all ions from atomic number 1 to 92.

C. Displacement Damage Evaluation

Displacement damage is cumulative damage resulting from displacement of atoms in a semiconductor lattice structure. These defects can cause material changes such as carrier lifetime shortening and mobility degradation.

A quantity analogous to the ionization dose, the damage dose, can be used to study displacement damage effects [16,17]. It is the energy that goes into displaced atoms per unit mass of material as opposed to the energy that goes into ionization. After transporting the incident ion energy spectra through shielding the damage dose is calculated

$$Damage\quad Dose = C\sum_{Z=1}^{92} \int_E NIEL(E)\varphi(E)dE \qquad (2)$$

where $NIEL(E)$ and $\varphi(E)$ are the transported particle Nonionizing Energy Loss (NIEL) [16,17] and fluence, respectively, as a function of energy, and C is a unit conversion. NIEL is the displacement damage analog of LET. The total deposited damage dose is a sum over all ions from atomic number 1 to 92.

D. *Single Event Effects Evaluation*

SEE are caused by single incident ions. They can result in either destructive effects such as single event latchup or non-destructive effects such as single event upset. Here we restrict our evaluation to single event upset. In calculating single event rates it is commonly assumed there is a sensitive volume that can be approximated by a rectangular parallelpiped (RPP). Incident ions are assumed to be isotropically incident. After passing through shielding, if an ion deposits an energy (or charge) greater than or equal to a threshold value in the RPP an upset is assumed to occur [2].

Ions incident on the RPP can cause an upset in 2 different ways. The first is by direct ionization. The second is by nuclear reactions. In the latter case this occurs if the nuclear reaction products deposit at least the threshold energy in the RPP. Our calculations have accounted for both direct ionization and nuclear reaction-induced upsets. They also account for slowing down of the incident ions as they traverse the RPP. This is an improvement over the commonly used CREME96 calculation [2].

III. Results

A. *Solar Particle Event Environment*

Figures 1-4 show results for the long-term solar energetic ion environment, emphasizing a confidence-level based approach for spacecraft designs. The figures give the differential particle fluence-energy spectra for protons, alpha particles, oxygen and iron ions, which are all major components of this environment. All calculations were done for an example of a 2-year mission during the solar maximum time period. Confidence levels shown range from 50% to 99%. A 99% confidence level is interpreted to mean there is a 99% chance the given fluence levels will not be exceeded during the 2-year mission. A 50% confidence level represents the average environment. In other words there is a 50% chance the environment will be better and a 50% chance the environment will be worse than this.

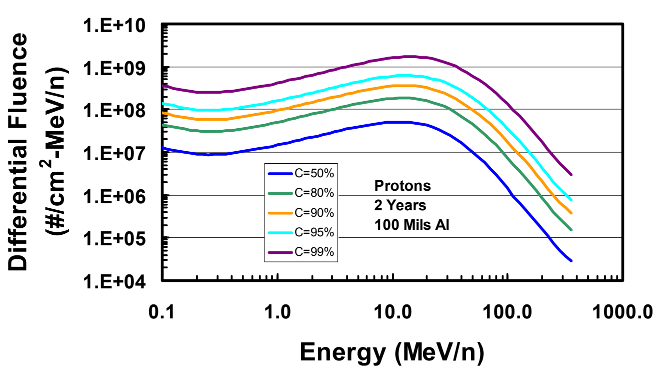

Fig. 1. Differential fluence-energy spectra for protons accumulated over a 2-year period during solar maximum at the 50, 80, 90, 95 and 99% confidence levels. Results are for shielding by 100 mils of aluminum in a solid sphere geometry.

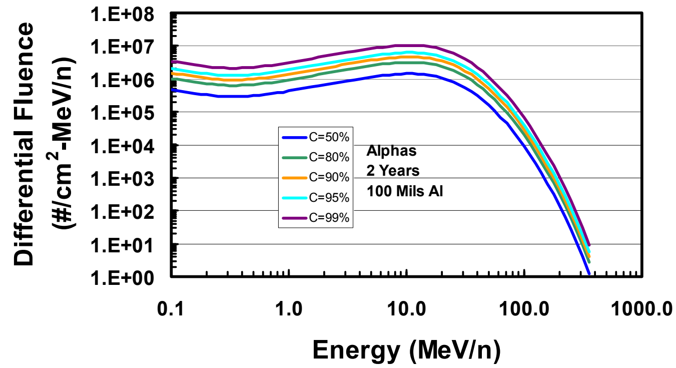

Fig. 2. Differential fluence-energy spectra for alpha particles accumulated over a 2-year period during solar maximum at the 50, 80, 90, 95 and 99% confidence levels. Results are for shielding by 100 mils of aluminum in a solid sphere geometry.

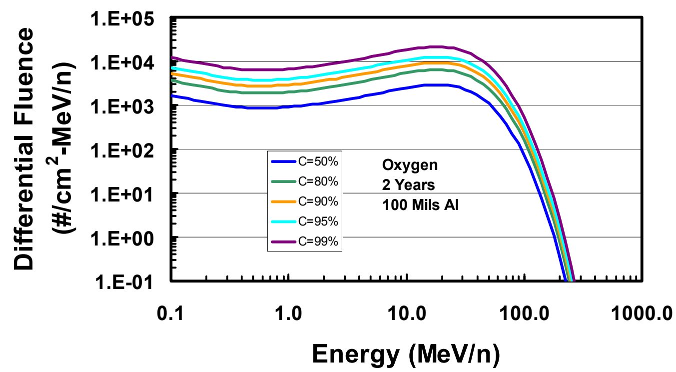

Fig. 3. Differential fluence-energy spectra for oxygen accumulated over a 2-year period during solar maximum at the 50, 80, 90, 95 and 99% confidence levels. Results are for shielding by 100 mils of aluminum in a solid sphere geometry.

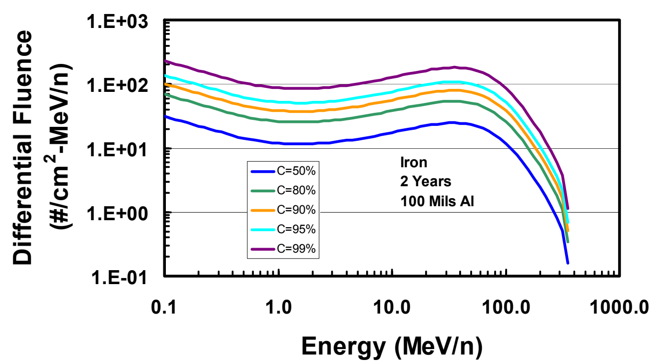

Fig. 4. Differential fluence-energy spectra for iron ions accumulated over a 2-year period during solar maximum at the 50, 80, 90, 95 and 99% confidence levels. Results are for shielding by 100 mils of aluminum in a solid sphere geometry.

The energy spectra in the figure extend to high enough energies that the high-energy fluxes are small compared to the background galactic cosmic ray fluxes at the same energy. At low energies the incident spectra now extend to 0.1 MeV/nucleon so there are no practical constraints for radiation effects applications of this model environment.

The LET metric has traditionally been a useful and convenient parameterization for SEE. It transforms the energy spectra of all elements of concern to a single curve of fluence vs. LET. Thus it also gives a good overall view of the environment. Figure 5 shows integral LET spectra for all solar particle event elements such as those shown in the first 4 figures over a range of confidence levels. The 50% confidence level would be appropriate to use for evaluating an average upset rate for solar particles. The 99% confidence level would be appropriate for a very conservative design estimate of the upset rate for solar particles.

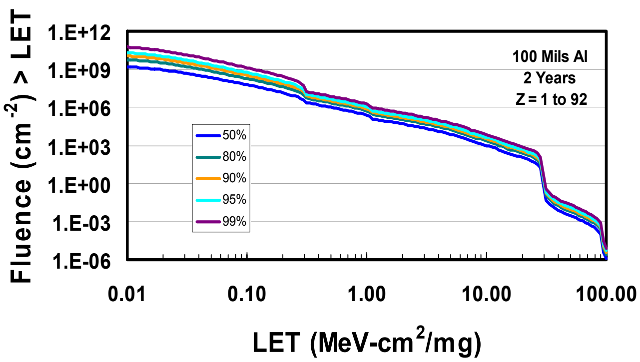

Fig. 5. Integral LET spectra for cumulative solar particle events over a 2-year solar maximum period at the 50, 80, 90, 95 and 99% confidence levels. Results are for shielding by 100 mils of Al in a solid sphere geometry and include elements from atomic number $Z = 1$ to 92.

B. Total Ionizing Dose

For radiation environments outside of planetary magnetic fields the dominant contribution to TID effects comes from the solar particle environment. Thus, it is particularly important to understand this for new exploration initiatives such as lunar missions. Figure 6 shows the cumulative dose contributed by each element due to solar particle events over a 2-year period with 100 mils of aluminum shielding. The 50% confidence level is representative of an average dose level.

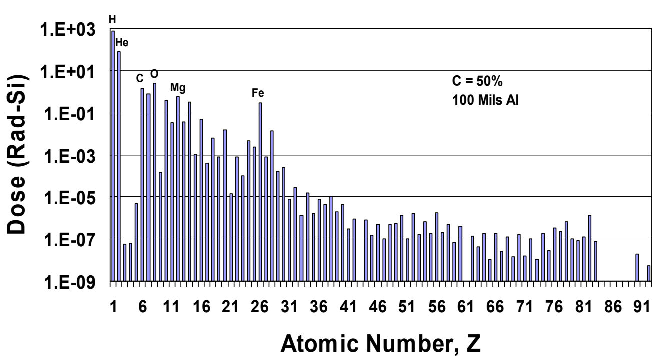

Fig. 6. Cumulative dose contributed by element for solar particle events over a 2-year period during solar maximum using 100 mils of aluminum shielding. Note the logarithmic scale for the y-axis.

The three largest dose contributions come from protons, alpha particles and oxygen. The alpha particle dose is about a 10% addition to the proton dose while it is reasonable to neglect the contribution for $Z > 2$ ions. This is consistent with the particle abundances shown in figures 1-4.

Results for the TID simulations are shown in figure 7 for a wide range of shielding thickness and confidence level. The effectiveness of the shielding is shown by the 50% confidence level. It is seen the dose behind 10 mils of aluminum is about 20 krad(Si) while for 100 mils it is reduced to about 1 krad(Si). The confidence level dependence illustrates the tradeoffs that can be evaluated for microelectronic component selection, for example. For a common design assumption of 100 mils of aluminum shielding, the expected dose level is 1 krad(Si). However, selection of a 1 krad(Si) hard part results in a 50% chance of failure before completion of the 2-year mission. If it is desired to reduce this failure level to 5%, the 95% confidence level is chosen and a part should be selected that is about 10 krad(Si) hard. One of the tradeoffs involved is the increased cost of the harder part.

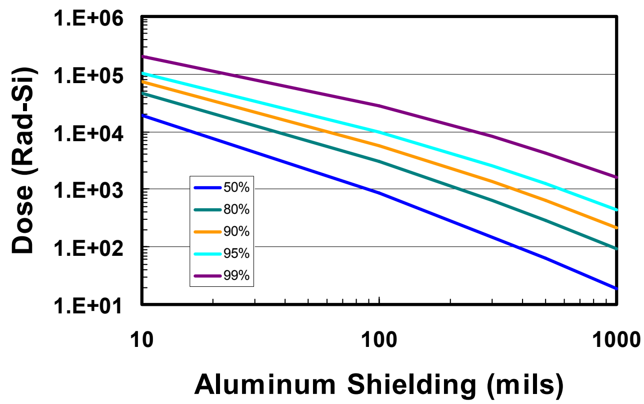

Fig. 7. TID deposited due to solar particle events in a silicon target as a function of confidence level and shielding thickness for a 2-year mission during solar maximum.

C. Displacement Damage

As discussed in section IIC, the evaluation of DD can be done in a way that is completely analogous to the evaluation of TID. The net result is a figure that is similar to figure 7 except that damage dose is plotted on the y-axis as a function of shielding thickness and confidence level. Similar to the case of ionizing dose the dominant contribution to DD effects comes from solar particles for missions outside of planetary magnetic fields such as lunar missions. These DD results will be discussed in the full length paper.

D. Single Event Upset Results

Single event upset (SEU) rates in space depend on many factors. Within the context of the calculations presented in section IID there is a strong dependence on the dimensions of the RPP, i.e., the volume that is sensitive to SEU. For these calculations an RPP with dimensions of 1 x 1 x 1 µm has been chosen, which is representative of state-of-the-art technology for memories. Figures 8 and 9 show results for long-term upset rates due to the solar particle event environment over a 2-year period during solar maximum. The results in figure 8 are for an RPP with 100 mils of Al shielding and figure 9 is for 300 mils of Al shielding. The y-axis shows the number of upsets that are expected to occur per bit during the 2-year mission as a function of the upset threshold energy in units of MeV. State-of-the-art commercial memories under development have upset thresholds on the order of 10s of keV. This clearly results in upset rates that are too high without any mitigation. On the other hand SEU hardened memories can have upset thresholds that are on the order of 1 MeV. In this case, a 1 Mbit memory is not likely to upset at all during the mission. However, the cost and speed of such memories are tradeoffs that must be balanced against the SEU rate. Another factor that is important to consider is the shielding. Note that the increased shielding for the 300 mil case can result in up to an order of magnitude reduction in the SEU rate for solar particle events. In addition the choice of confidence level can result in a SEU rate that differs by as much as 2 orders of magnitude depending on the type of memory under consideration.

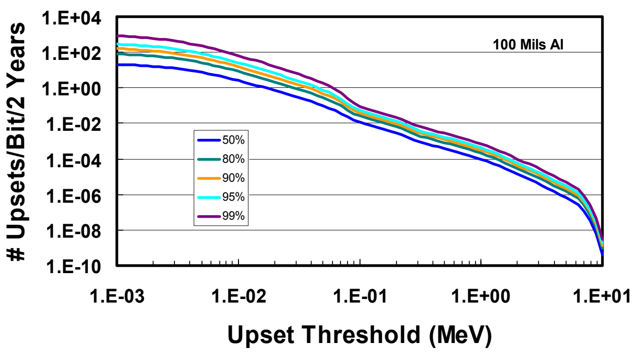

Fig. 8. Number of upsets per bit per 2 years as a function of upset threshold for a memory bit having a sensitive volume of 1 x 1 x 1 µm. Results are shown for various confidence levels and for 100 mils of aluminum shielding.

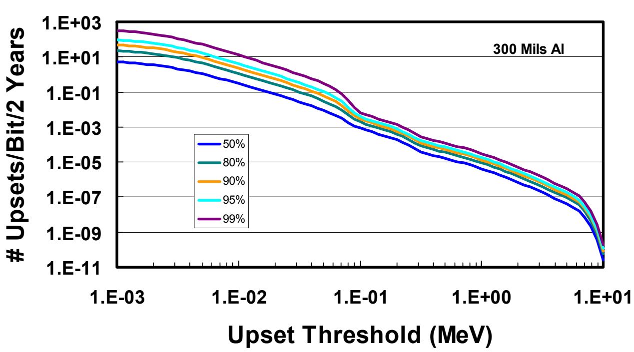

Fig. 9. Number of upsets per bit per 2 years as a function of upset threshold for a memory bit having a sensitive volume of 1 x 1 x 1 µm. Results are shown for various confidence levels and for 300 mils of aluminum shielding.

The fluxes of radiations that are significant for producing SEE also depend on the time period during the solar cycle. During solar minimum galactic cosmic ray fluxes are very important and are likely the dominant factor. During solar maximum it has only been recently recognized that the solar particle event contribution is probably at least as important as the galactic cosmic ray contribution, even though the latter are difficult to shield against [5]. It is hoped that these results shed further light on our ability to design space systems for these environments.

IV. Summary

In this work we have further developed a stochastic model of cumulative solar heavy ion fluences during the solar maximum time period. This adds to the available space radiation environment design tools and is important for a number of reasons. The solar maximum time period is generally regarded to extend over 7 years out of every 11 year solar cycle so the model is applicable to many missions. The model can be used as input for different problems such as determining exposure of space systems and instrumentation, as well as astronaut exposure. In this paper it has been applied to component selection criteria for the design of space systems. This allows component selection to be made by the system designer using a confidence-level based approach so that risk-cost-performance tradeoffs can be more thoroughly evaluated.

References

[1] R.A. Nymmik, M.I. Panasyuk and A.A. Suslov, “Galactic Cosmic Ray Flux Simulation and Prediction”, Adv. Space Res., Vol. 17, No. 2, (2)19-(2)30 (1996).

[2] A.J. Tylka et al., “CREME96: A Revision of the Cosmic Ray Effects on Microelectronics Code”, IEEE Trans. Nucl. Sci., Vol. 44, 2150-2160 (1997).

[3] G.D. Badhwar and P.M. O’Neill, “Galactic Cosmic Radiation Model and Its Applications”, Adv. Space Res., Vol. 17, No. 2, (2)7-(2)17 (1996).

[4] S. Bourdarie and M.A. Xapsos, “The Near-Earth Space Radiation Environment”, IEEE Trans. Nucl. Sci., accepted for publication.

[5] M.A. Xapsos, C. Stauffer, T. Jordan, J.L. Barth and R.A. Mewaldt, “Model for Cumulative Solar Heavy Ion Energy and Linear Energy Transfer Spectra”, IEEE Trans. Nucl, Sci., Vol. 54, No. 6 (Dec. 2007).

[6] J.H. King, “Solar Proton Fluences for 1977-1983 Space Missions”, J. Spacecraft, Vol. 11, pg. 401-408 (1974).

[7] J. Feynman, G. Spitale, J. Wang and S. Gabriel, “Interplanetary Fluence Model: JPL 1991”, J. Geophys. Res., Vol. 98, pg. 13281-13294 (1993).

[8] M.A. Xapsos, C. Stauffer, G.B. Gee, J.L. Barth, E.G. Stassinopoulos and R.E. McGuire, “Model for Solar Proton Risk Assessment”, IEEE Trans. Nucl. Sci., Vol. 51, pg. 3394-3398 (2004).

[9] A.J. Tylka, W.F. Dietrich and P.R. Boberg, “Probability Distributions of High-Energy Solar-Heavy-Ion Fluxes from IMP-8: 1973-1996”, IEEE Trans. Nucl. Sci., Vol. 44, pg. 2140-2149 (1997).

[10] M.A. Xapsos, G.P. Summers, J.L. Barth, E.G. Stassinopoulos and E.A. Burke, “Probability Model for Cumulative Solar Proton Event Fluences”, IEEE Trans. Nucl. Sci., Vol. 47, No. 3, pg. 486-490 (June 2000).

[11] R.A. Mewaldt et al., Space Sci. Rev., Vol. 130, pg. 323 (2007).

[12] D.V. Reames, “Solar Energetic Particles: Sampling Coronal Abundances”, Space Sci. Rev., Vol. 85, pg. 327-340 (1998).

[13] N. Grevesse and A.J. Sauval, “Standard Solar Composition”, Space Sci. Rev., Vol. 85, pg. 161-174 (1998).

[14] D.V. Reames, “Particle Acceleration at the Sun and in the Heliosphere”, Space Sci. Rev., Vol. 90, pg. 413-491 (1999).

[15] NOVICE Software Documentation, E.M.P. Consultants, Gaithersburg, MD, 2006.

[16] C.J. Marshall and P.J. Marshall, “Proton Effects and Test Issues for Satellite Designers – Part B: Displacement Effects”, IEEE NSREC Short Course, IEEE Publishing Services, Pascataway, NJ, July 1999.

[17] R.J. Walters, S.R. Messenger, G. P. Summers and E.A. Burke, “Solar Cell Technologies, Modeling and Testing”, IEEE NSREC Short Course, IEEE Publishing Services, Pascataway, NJ, July 2004.